Science of the Total Environment 659 (2019) 41–52

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Life cycle analysis of copper-gold-lead-silver-zinc beneficiation process

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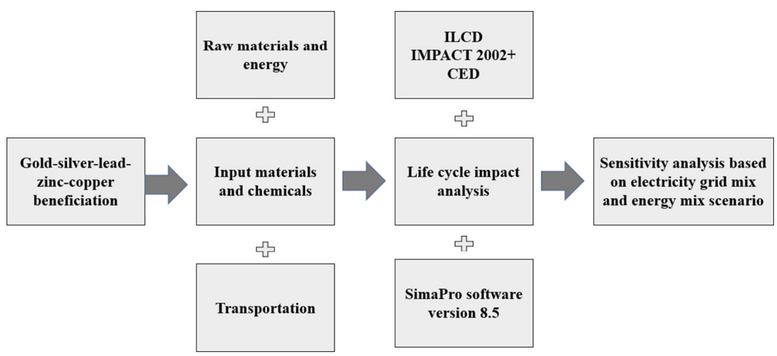
HIGHLIGHTS

- Life cycle assessment of gold-silver-lead-zinc-copper beneficiation is carried out.
- LCA is conducted through SimaPro software using ILCD, IMPACT 2002+, and CED method.
- Gold-silver beneficiation are higher impact as compared to lead-zinc.
- Notable impact categories are ionising radiation, acidification, eutrophication, and human health.
- Electricity and fossil fuel consumption are the dominant factors causing the impacts.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 November 2018
Received in revised form 20 December 2018
Accepted 21 December 2018
Available online 23 December 2018

Editor: Deyi Hou

Keywords:
Beneficiation
Gold
Silver
Lead
Zinc
Copper

ABSTRACT

Gold, silver, lead, zinc, and copper are valuable non-ferrous metals that paved the way for modern civilisation. However, the environmental impacts from their beneficiation stage was always overlooked. This paper analysed the life cycle environmental impacts from the beneficiation process of gold-silver-lead-zinc-copper combined production. The analysis is conducted by utilising the SimaPro software version 8.5. The life cycle assessment methodologies followed are the International Reference Life Cycle Data System (ILCD) method, the IMPACT 2002+ method, and the Cumulative Energy Demand Method (CED). The most significant impact categories are ecotoxicity, climate change, human toxicity, eutrophication, acidification, and ozone depletion among nearly 15 impact categories which are assessed in this study. The analysis results from the ILCD method indicate that there is a noteworthy impact on ionising radiation caused by the beneficiation process. Out of the five metals considered, gold and silver beneficiation impacts the most while lead zinc beneficiation impacts the least. Gold beneficiation has most impacts on the category of climate change and ecosystems. Other major impact categories are ionising radiation, terrestrial eutrophication, photochemical ozone formation, human toxicity, and acidification. The IMPACT 2002+ method shows the overall impact is on ecosystem quality and human health from this combined beneficiation process, dominantly from gold silver beneficiation. The life-cycle inventory results show that the blasting process and the amount of electricity consumption in the beneficiation process contribute to cause significant amount of environmental impacts. The comparative impact results are presented and discussed in detail in this paper. Sensitivity analyses are presented based on various electricity grid-mix scenarios and energy-mix scenarios, and the results suggest that electricity grid mix has a dominant effect over the fossil-fuel mix. This paper also highlights the potential steps which could cut down the environmental effects by integrating renewable-energy technologies.

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https://doi.org/10.1016/j.scitotenv.2018.12.318

1. Introduction

Non-ferrous metals like gold, silver, lead, zinc, and copper have their unique properties and use. Copper is a popular conductor of thermal energy and electricity, used commercially for making alloys and building materials. Copper is used for making electronic devices and wiring due to its properties like ductility and softness (Davis, 2001; Norgate and Rankin, 2000). Gold is a popular precious metal for making jewellery, medicine and electronics (Canda et al., 2016; Haque and Norgate, 2014). Like copper, gold is also ductile, soft and bright (Corti and Holliday, 2004; Northey et al., 2014). Lead metals are malleable making them useful for making bullets, batteries, or architectural metals (Christie and Brathwaite, 1995). Due to the high mechanical and electrical conductivity, silver is used for making electronic devices, silverware, and jewellery (Lee et al., 2017). Zinc is an alloying metal, abrasive agent, and a component to make batteries that have similar chemical properties and applications to lead (Christie and Brathwaite, 1995; Norgate et al., 2007).

Though all these materials have their specific properties and applications, they have unique environmental impacts due to the emission of chemical compounds to air, soil, water, and environment. Copper is a threatening element for the marine environment and species and is also harmful for deforestation (Ashraf et al., 2015). Gold mining releases a considerable amount of wastes per year which are responsible for soil or water pollution. Underground rock also causes acid mine drainage from gold mining (Fashola et al., 2016). Lead particles can be accumulated in plants or soils which remain unchanged thus leading to deforestation (Zuazo and Pleguezuelo, 2008). Silver mining causes the formation of sinkhole, soil or environment pollution, or can cause biodiversity (Farjana et al., 2018a). During zinc mining and extraction, its particles emit into the environment and make pollution (Wuana and Okieimen, 2011).

Among the previous research work based on life cycle assessment of non-ferrous metal processing, there are a few notable research contributions which addressed the environmental impacts from the mining, beneficiation, and refining processes. Many researchers tried to address the LCA analysis on copper, gold, or zinc mining (Memary et al., 2012; Norgate and Haque, 2012; Norgate, 2001; Norgate and Rankin, 2000; Qi et al., 2017; Van Genderen et al., 2016). The specific details about these studies are discussed in Table 1 below. Though copper, gold, zinc, lead, or silver produce with by-products, their beneficiation process always produces some by-products, whatever the quantity is. However, addressing the allocation of the byproducts, their inputs, outputs, and emissions are quite different in the previous research works. Memary et al. conducted an LCA analysis of copper production which had gold and silver metals as a by-product (Memary et al., 2012). Northey et al. conducted their copper-based LCA analysis using weighted data to show relative environmental results in comparison with other metals. Allocation is based on the annual average prices of

Table 1
Key features of the existing research papers on LCA of copper, gold, zinc.

Metal	Author	Objectives	Impact categories	Responsible process steps/materials	Analysis results
Copper	Norgate (Norgate and Rankin, 2000)	Assessed the pyrometallurgical and hydrometallurgical processing routes, number of process variables and ore grades.	Energy consumption, greenhouse-gas emission, acidification potential	Hydrometallurgical production has a higher impact on the environment.	GWP 3.3 CO_2 eq./kg Energy consumption 33 MJ/kg Acidification potential 0.04 kg SO_2 eq/kg
	Memary et al. (Memary et al., 2012)	Analysis of copper production based on time series in Australia from 1940 to 2008 (5 largest mines)	Photochemical ozone depletion potential, global-warming potential, acidification potential	Ore grade, differences in technology, and regional energy sources impact mainly on environmental effects.	Carbon footprint varies from 2.5 to 8.5 kg CO_2 eq/kg.
	Norgate (Norgate, 2001)	Life cycle analysis of various copper mining technologies using hydrometallurgical processes	Energy consumption, greenhouse-gas emission, acidification potential	Hydrometallurgical processes involving the electrowinning processes have the most substantial energy consumption due to high power consumption	From 4.3 to 8.9 kg CO_2 eq./kg for hydrometallurgical processes. From 1.5 to 4.2 kg CO_2 eq./kg for pyrometallurgical processes.
	Northey et al. (Northey et al., 2013)	Quantified the environmental footprint caused by the copper production processes using sustainability reporting	Energy consumption, greenhouse-gas emission, water intensity	The variation of results from one company to another due copper mining, ore grade, the source of energy, and reporting procedure of companies; which should be clarified in the company reports.	From 1 to 9 t CO_2 eq./Cu greenhouse gas emissions and around 70.4 KL/t Cu water footprint.
Gold	Chen et al. (Chen et al., 2018)	Assessed the environmental impacts of the gold production of China on ecosystems and human health.	Several major impact categories are assessed through the ReCipe method	Major impacts are due to ore mining, energy consumption.	Climate change effect is 5.55E7 kg CO_2 eq A major part of the impact is on the metal depletion category.
	Norgate et al. (Norgate and Haque, 2012)	Life cycle environmental impact assessment of gold production for two types of ores has been conducted.	Embodied energy, greenhouse-gas footprint is assessed.	With refractory ore the emissions are 50% higher than those with non-refractory ores due to excess material and technology use. Mining and comminution stage effects mostly due to electricity consumption.	200,000 GJ/t Au 18,000 t CO_2 eq/t Au 260,000 t water/t Au 1,270,000 t waste/t Au
Zinc	Genderen et al. (Van Genderen et al., 2016)	Life cycle analysis of zinc production has been conducted with datasets from 24 mines and 18 smelters.	Global warming, acidification, eutrophication, photochemical ozone creation, primary energy demand is assessed.	65% of environmental burdens from global zinc production are due to smelting, 30% is from mining, and 5% is from transportation.	Primary energy demand is 37,500 MJ/t of Zn Climate change effect is 2600 kg CO_2 eq/t.
	Qi et al. (Chen et al., 2018)	Life cycle analysis of zinc production in China is conducted while datasets are from national statistical dataset inventory and process-based Life Cycle Inventory.	Assessed several impact categories using the ReCipe method including climate change, human toxicity, freshwater eco-toxicity.	A major contributor is zinc ore mining & energy consumption.	Climate change 6.12E3 kg CO_2 eq. Marine ecotoxicity 17 kg 1,4-DB eq. Metal depletion 3.58E3 kg Fe eq.

copper or the London metal exchange rate from 2009 to 2010. It is also mentioned that the non-metallic byproducts included in this study are not weighted for their analysis (Northey et al., 2013). Haque et al. analyses the life cycle environmental impacts of gold with the assumption that gold also contains silver. They used both mass and revenue based allocation as the Rio Tinto company employed mass and revenue based allocation for concentration and refining (Norgate and Haque, 2012). Genderen et al. analysed the LCA of zinc based on mass-based allocation for allocating the inputs and outputs among the various coproducts during the process (Van Genderen et al., 2016). None of the existing research considered all the base metals for co-production for environmental impact analysis from the beneficiation process. The previous researches focused on a primary principle metal either from a complete production process with either mass or revenue-based allocation for the byproduct metals. In the present research, particularly the beneficiation process is considered with the coproducts, where environmental effects are assessed through >15 impact categories. In the previous works, mostly the global warming potential, acidification potential, and energy consumption are analysed. Their lack of focus persists in many significant impact categories like ecotoxicity, eutrophication, or ionising radiation. These limitations of previous studies are also covered here. Moreover, there was no significant LCA research based on lead or silver production processes, so this is another notable aspect of the present work.

The key features of the existing LCA work on copper, gold, or zinc production processes are described in Table 1 below.

The reasons behind these environmental issues vary from one mining step to another. From extraction, development, mining, beneficiation, refinery to tailing disposal, each step has separate heat and energy requirements and different technologies. These arrangements make them act differently towards the environment. To assess the environmental impacts caused by different stages, it is necessary to calculate the life-cycle environmental impacts on the beneficiation stage of mining. Life cycle environmental impact analysis is a powerful tool which aims to analyse the details of environmental effects from cradle to gate of a product, system, or process. In this research, we are focused on the sustainability assessment of the beneficiation process of gold-silver-lead-zinc-copper mines. In Section 2, the beneficiation process and its details are outlined. Section 3 analyses the life-cycle assessment methodology. Section 4 outlines the comparative analysis results. Section 5 is based on the discussion about significant findings, key techniques to reduce impacts from beneficiation process and how to improve those. Section 6 gives concluding remarks.

2. Gold-silver-lead-zinc-copper beneficiation process

Beneficiation includes crushing, grinding, gravity concentration, and flotation concentration. Beneficiation is followed by processing activities such as smelting and refining. The beneficiation process begins with milling, which is followed by flotation for further beneficiation.

2.1. Milling operation

At the first stage, extracted ores undergo the milling operation to produce uniformly sized particles for crushing, grinding, wet or dry concentration. The type of milling operable in a certain plant is chosen by the capital investment and economics. The degree of crushing or grinding which is required for further beneficiation is dependent on capital. Crushing is a dry operation which only involves dust control using water spray (Drzymala, 2007). A primary or jaw crusher is located at the mine site and reduces the particle diameter of the ores into <6 in. The crushed ore is then transported to the mill site for crushing, grinding, classification, and concentration. The second stage, grinding is a wet operation which requires initial flotation and water to make a slurry. The hydro-cyclone operates between each grinding operation to classify the type of particles: fine or coarse (Long et al., 1998).

2.2. Flotation

This process is used to adhere ore mineral or a group of minerals with the air bubbles after involving chemical reagents in operation. Chemical reagents got reacted with the desired mineral in the flotation process. The effectiveness of the flotation technique is dependent on four factors: the degree of oxidation of the ore, the number of copper minerals present, the nature of the gangue, and the presence of iron sulphides. There are some other important factors such as the particle size, minerals compatible with the reagents, and the condition of the water. Conditioners and regulators might be used during or after the milling time for ore treatment (Drzymala, 2007). Flotation is an effective method to concentrate the targeted elements existed in minerals based on the difference in physicochemical properties of various mineral surfaces. It can easily separate copper (Feng et al., 2018b), lead (Feng et al., 2017a), zinc (Feng and Wen, 2017), tin (Feng et al., 2017b) minerals from gangue minerals by addition of flotation reagents.

2.3. Roasting and sintering

The concentrates of minerals must go through pyrometallurgical methods like smelting and refining. However, before these steps, the concentrates may require roasting and sintering which depends on the processing method. The ore concentrate undergoes partial fusion which turns it into agglomerated material suitable for processing operations (Drzymala, 2007). The sintering operation consists of blending, sintering, cooling, and sizing. At first, the raw material concentrates are blended with moistures in mills, drums, or pans. This step is called blending. In the next step, the concentrate feed is fired or sintered and then cooled (Long et al., 1998). The sinter gets crushed with being cool. Then the concentrate will be graded. After grading, it is crushed to produce a smaller sinter product. In roasting, gas-solid reactions are involved at elevated temperatures, which purify the metal by treating it with hot air (Shedd, 2016).

3. Life cycle analysis

Life-cycle analysis is an internationally recognised standardised process based on ISO 14040. ISO 14040 is composed of four major steps of impact analysis: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation of the results (Awuah-Offei and Adekpedjou, 2011; Lima et al., 2018; Mahmud et al., 2018a, b, c, d; Zhang et al., 2018).

3.1. Goal and scope

The goal of this research work is to analyse the cradle-to-gate environmental effects of the gold-silver-lead-zinc-copper beneficiation process, thus comparing their impacts under several impact categories. The scope of this work is the environmental emissions which are generated or emitted from the milling operation, flotation, roasting, and sintering. The materials, energy (renewables and non-renewables), fossil fuels used for process heat generation, organic and inorganic chemicals are considered as material inputs or inputs from nature. On the other hand, the emissions to soil, water (groundwater or other water resources), air, and the final production wastes are considered as outputs of the beneficiation process (Farjana et al., 2018d).

Table 2 shows the life-cycle inventory inputs and outputs which include fuels, renewable and non-renewable energies used for the beneficiation process and electricity generation, materials, organic and inorganic chemicals, emissions to air, soil, water (groundwater resources and other forms of water resources) and final waste emissions.

Table 2
Lifecycle inventory datasets-inputs and outputs.

	Copper	Gold	Lead	Silver	Zinc	Unit
Inputs						
Zn 0.63%, Au 9.7E-4%, Ag 9.7E-4%, Cu 0.38%, Pb 0.014%, in ore, in ground	1.1	1.1	1.1	1.1	1.1	kg
Water, salt, ocean	0.019	68.992	0.005	1.178	0.008	m^3
Water, well, in ground	0.001	5.411	0.0004	0.092	0.0006	m^3
Water, river	0.008	31.113	0.002	0.531	0.0037	m^3
Electricity, medium voltage	3.219	11,289.23	0.883	192.788	1.35	kWh
Hard coal	1.77	6209.009	0.485	106.032	0.742	MJ
Diesel fuel	0.965	3386.75	0.264	57.836	0.405	MJ
Natural gas	0.482	1693.375	0.132	28.918	0.202	MJ
Heavy fuel oil	0.643	2257.768	0.176	38.556	0.27	MJ
Blasting	0.115	406.48	0.031	6.941	0.048	kg
Transport, lorry > 16 t	0.013	46.249	0.003	0.789	0.005	tkm
Transport, freight	0.107	378.217	0.029	6.458	0.045	tkm
Mine, gold-silver-zinc-lead-copper	1.12E-10	3.94E-07	3.08E-11	6.72E-09	4.71E-11	p
Tap water	3E-04	1.352	1E-04	0.023	1.6E-04	kg
Sodium cyanide		27.961		0.47		kg
Limestone		62.559		1.053		kg
Sodium hydroxide, 50% in H_2O		11.524		0.194		kg
Zinc, primary		2.864		0.048		kg
Charcoal		16.791		0.282		kg
Sulphuric acid, liquid		0.658		0.011		kg
Hydrochloric acid, 30% in H_2O		13.499		0.227		kg
Outputs						
Copper	1.04E-07	3E-04	2.85E-08	6.23E-06	4.36E-08	kg
Carbon dioxide, fossil	0.018	65.036	0.005	1.11	0.007	kg
Lead	3.38E-08	1E-04	9.28E-09	2.02E-06	1.42E-08	kg
Zinc	2.87E-08	1E-04	7.88E-09	1.72E-06	1.2E-08	kg
Heat, waste	11.591	40,640.21	3.179	694.019	4.861	MJ
Copper, ion	1.42E-06	0.004	3.9E-07	8.5E-05	5.96E-07	kg
Lead	7.62E-07	0.002	2.09E-07	4.56E-05	3.2E-07	kg
Zinc, ion	1.21E-05	0.042	3.33E-06	7E-04	5.09E-06	kg
Disposal, sulfidic tailings	4.087	14,332.72	1.137	1.137	1.137	kg

3.2. Functional unit

For this analysis, 1 kg of each of the coproducts of each metal is considered here to be produced from the beneficiation process, that is the purified ore at the end of the mine concentrating stage.

3.3. System boundaries

LCA of the nonferrous metal beneficiation processes includes ore from the mine, the ore concentration, transportation, and smelting. This study does not have any intention to include the end-of-life product stages or environmental emissions for these non-ferrous metals. A cradle-to-gate LCA analysis has been performed which is focused particularly on the metal-beneficiation process. Fig. 1 describes the system boundary followed in the present research for LCA analysis. Fig. 2 shows the material flows from the non-ferrous metal beneficiation process.

3.4. Software and database

In the third stage of life-cycle analysis, life-cycle impact analysis is carried out using SimaPro software version 8.5. There are few other standard software available for LCA analysis such as Gabi, OpenLCA,

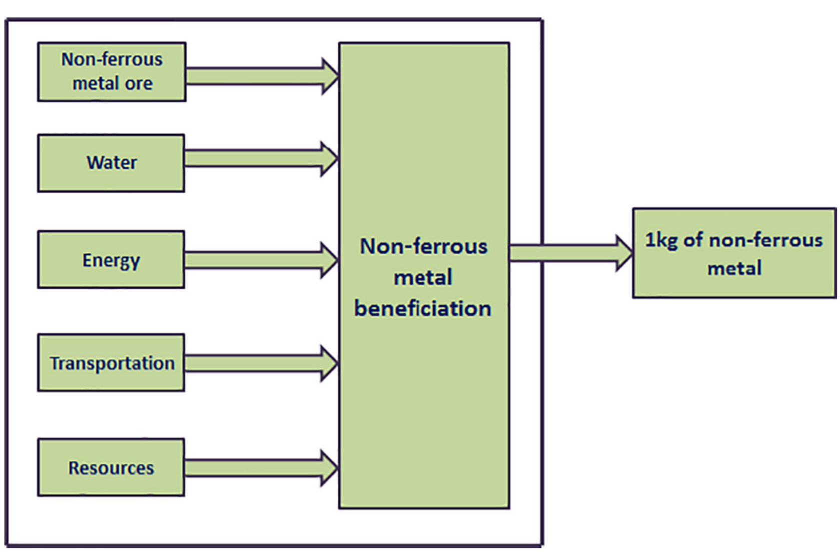

Fig. 1. System boundary diagram for LCA analysis.

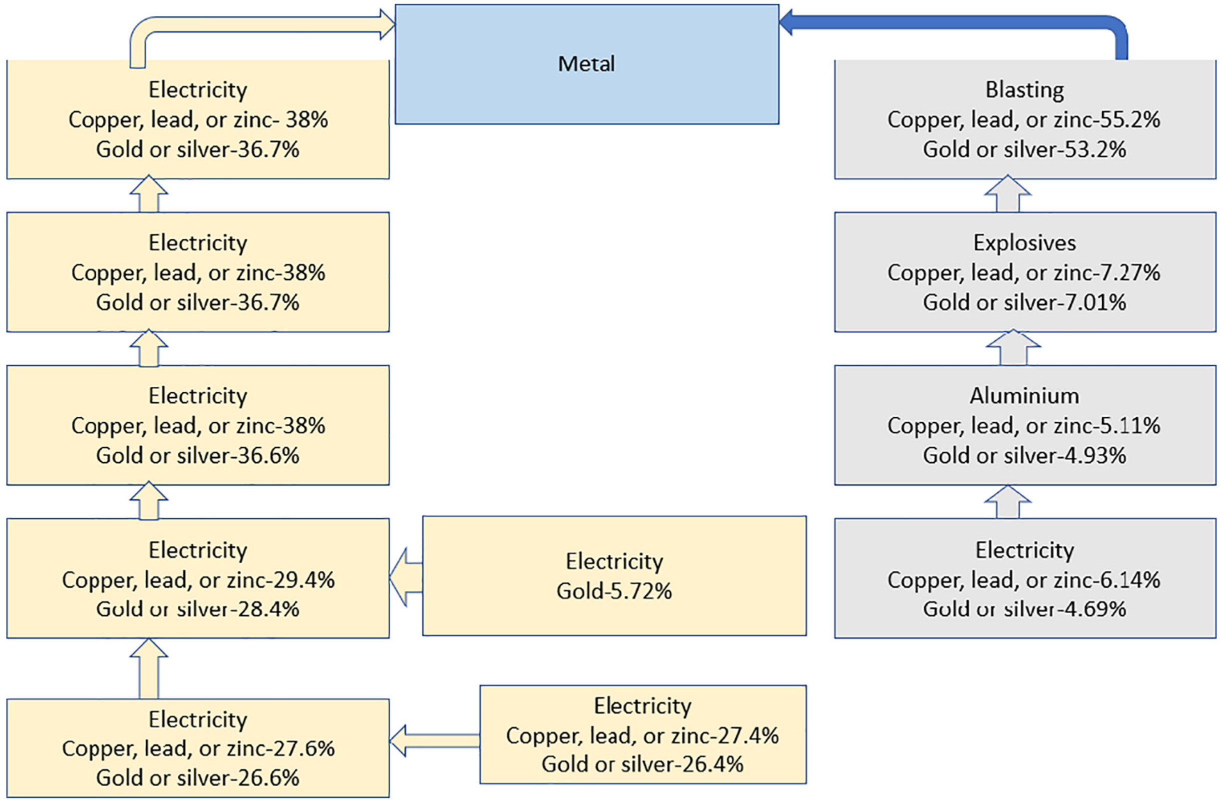

Fig. 2. Material flow diagram.

and Umberto. However, SimaPro is very well resourced with latest datasets and most widely used for conducting LCIA focused on metal mining industries. SimaPro software provides easy access and integrity with renowned and validated databases like EcoInvent, USGS, and AusLCI which contains numerous datasets of mining and mineral processing industries. This feature is limited to other available software. However, EcoInvent can be purchased separately and integrated with any software in use, like for Gabi. The relevant datasets originated from databases and literature are considered here that is from "Lifecycle inventories for metals and methodological approaches" by Classen et al. (Althaus and Classen, 2005).

3.5. Geographical coverage

The geographical coverage for the original dataset is Sweden; however, for the ease of analysis, it is assumed that geographical or climate-related factors are negligible here. Also, it is hard to compare among the datasets used in the present research and the previous researches because most of them considered the whole mining process from extraction to refining as a unit process (Farjana et al., 2018a; Mahmud et al., 2018a; Mahmud et al., 2018a, b, c, d). There is no research specifically focused on the beneficiation process. Also, lack of a research focus existed in the LCA of the silver or lead mining processes. However, in the later stages of this research, sensitivity analysis based on the electricity grid mix of different power associations in Europe and the energy mix of fossil fuels are presented to justify the impact of the differences of energy on gold-silver-lead-zinc-copper beneficiation process.

3.6. Allocation

Gold, silver, lead, zinc, and copper- all the non-ferrous metal coproducts are considered in this analysis. The revenue-based allocation approach is followed here, to distribute the process material inputs and outputs, emissions, wastes, and other flows associated with this process. The details of the allocation techniques can be found in the SimaPro manual (Goedkoop et al., 2014).

3.7. LCIA methodology

This subsection shows the impact-analysis results using the International Reference Life-cycle Data System (ILCD) method under fourteen major impact categories. This midpoint indicator-based method analysed the impacts on climate change, ecotoxicity, human toxicity, eutrophication, acidification, land and water use (JRC European Commission, 2011; Mahmud et al., 2018a, b, c, d). In the later stages, a comparative life-cycle analysis among all the non-ferrous metals involved in the beneficiation process is done. The Cumulative Energy Demand (CED) method assesses fuel consumption in the process or system of processes under LCA consideration. The characterisation factors for long-term emissions are set to zero, as per the implicit requirements from the European Commission. Each recommended impact category have been given equal weight. The full title for the ILCD method is "ILCD recommendations for LCIA in the European Context". This method contains the best practices provided by the European Commission among the several LCIA methodologies across the impact categories, because no best-practice methods have been developed based on the recommendation (European Commission – Joint Research Centre – Institute for Environment and Sustainability, 2010; Mahmud et al., 2018a, b). Fig. 3 illustrates the major impact categories and their contribution area for each LCIA method used in this study.

4. Results

Table 3 and Fig. 4 describe the comparative life-cycle assessment results among the five non-ferrous metals involved in the couple production: gold, silver, lead, zinc, and copper. The results indicate that among the five metals, the gold beneficiation process is the most

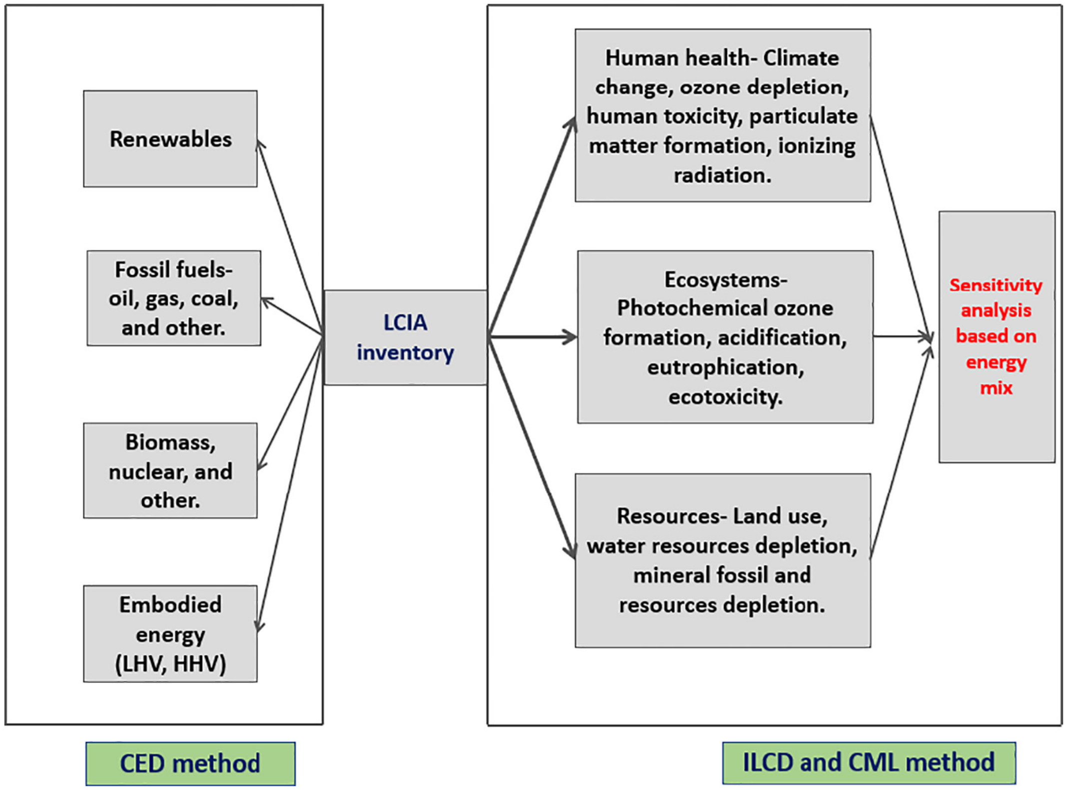

Fig. 3. Major impact categories assessed by LCA study here.

detrimental one towards sustainability. The significant impact categories are ionising radiation, photochemical ozone formation, terrestrial eutrophication, acidification, climate change, marine eutrophication, freshwater eutrophication, and water resources depletion. Blasting is the most environmentally impactful process of the beneficiation process, which impacts mostly onto terrestrial eutrophication, marine eutrophication, and acidification. Electricity consumed in copper beneficiation is the second-largest impactful element which mostly affects on ionising radiation. Carbon-14 emission from medium-voltage electricity generation is responsible for ionising radiation.

On the other hand, blasting releases nitrogen oxides which cause terrestrial eutrophication, marine eutrophication, and acidification. The most significant environmental impact is on ionising radiation, which is 2148.9 kBq U235 eq from gold beneficiation. The next one is terrestrial eutrophication which is 172.22 kg NMVOC eq. The photochemical-ozone-formation effect is 3335.388 kg C deficit. The acidification potential is 0.019 CTUe. The human-toxicity non-cancer effects are counted as 3.88E-04 CTUh. From the gold beneficiation, the human-toxicity-cancer effects are counted as 2.37E-05 CTUh. The impacts from marine eutrophication are 951.064 molc N eq. Lastly, the particulate-matter effect is 10.697 kg PM 2.5 eq.

On the other hand, lead beneficiation is the most sustainable to the environment. The most significant environmental impact is on ionising radiation, which is 0.168 kBq U235 eq from lead beneficiation. The next one is terrestrial eutrophication which is 0.013 kg NMVOC eq. The photochemical ozone formation effect is 0.12 kg C deficit. The acidification potential is 1.52E-06 CTUe. The human toxicity non-cancer effects are counted as 1.97E-08 CTUh. From the lead beneficiation, the human toxicity-cancer effects are counted as 1.75E-09 CTUh. The impacts from marine eutrophication are 0.074 molc N eq. Lastly, the particulate matter effect is 8.3E-04 kg PM 2.5 eq. Environmental impacts from silver beneficiation come next to gold, while copper and zinc beneficiation

Table 3
Comparative LCA results of beneficiation process-ILCD method.

Label	Unit	Copper	Gold	Lead	Silver	Zinc
CC (climate change)	kg CO_2 eq	0.97	3640.55	0.268	62.12	0.41
OD (ozone depletion)	kg CFC-11 eq	6.06E-08	2.25E-04	1.66E-08	3.84E-06	2.54E-08
HTNCE (human toxicity, non-cancer effects)	CTUh	7.17E-08	3.88E-04	1.97E-08	6.59E-06	3.01E-08
HTCE (human toxicity, cancer effects)	CTUh	6.37E-09	2.37E-05	1.75E-09	4.05E-07	2.67E-09
PM (particulate matter)	kg PM 2.5 eq	3E-03	10.697	8.3E-04	0.18	1.2E-03
IRHH (ionising radiation HH)	kBq U235 eq	0.613	2148.9	0.168	36.697	0.257
AP (acidification)	CTUe	5.53E-06	0.019	1.52E-06	3.3E-04	2.32E-06
TE (terrestrial eutrophication)	kg NMVOC eq	0.048	172.22	0.013	2.94	0.02
FE (freshwater eutrophication)	molc H+ eq	0.054	191.714	0.014	3.273	0.022
ME (marine eutrophication)	molc N eq	0.27	951.064	0.074	16.24	0.113
FE (freshwater ecotoxicity)	kg P eq	8.08E-04	2.84	2.22E-04	0.048	3.39E-04
LU (land use)	kg N eq	0.016	59.25	0.004	1.011	0.007
WRD (water resource depletion)	CTUe	0.292	1193.144	0.08	20.33	0.122
POF (photochemical ozone formation)	kg C deficit	0.438	3335.388	0.12	56.539	0.183
MFRRD (mineral, fossil & ren resource depletion)	m^3 water eq	0.005	19.882	1.4E-04	0.339	2.2E-03

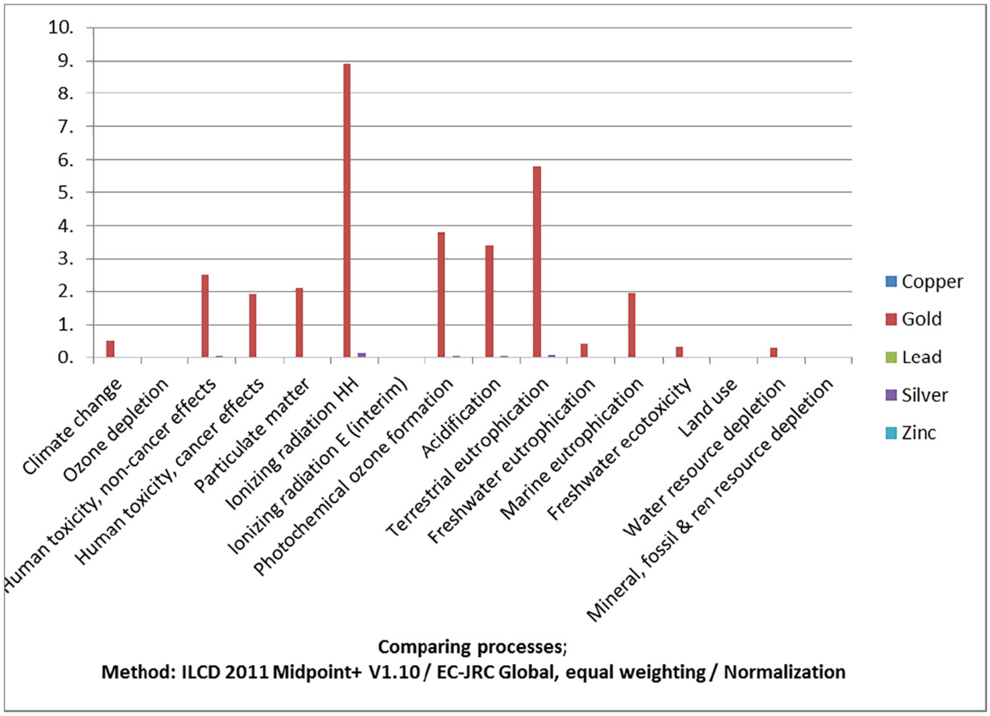

Fig. 4. Analysis results from ILCD method-normalized results.

shows similar results following silver beneficiation. Table 3 shows the characterized results, while Fig. 4 shows the normalized results to compare among the impacts caused by the coproduct metals.

Table 4 and Fig. 5 describe the LCIA results from the CED method. The analysis results from the cumulative energy demand method show that the highest environmental effects are caused by nuclear energy consumption and coal consumption which might have been due to electricity generation. Analysis results showed that gold beneficiation consumed the highest amount of nuclear fuel, that is 54,965.26 MJ LHV. Then renewable energy consumption is 17,551.69 MJ LHV. Embodied energy consumption is 120,798.3 MJ LHV and 123,234.2 MJ HHV. Coal consumption generates 15,431 MJ LHV heat while the smallest amount of heat is from gas that is 8903 MJ LHV. The CED method shows similar results to the ILCD method that lead beneficiation consumes the lowest amount of energy. Lead beneficiation consumed the lowest amount of nuclear fuel that is 4.295 MJ LHV. Then renewable energy consumption is 1.368 MJ LHV. Embodied energy consumption is 9.082 MJ LHV and 9.2 MJ HHV. Coal consumption generates 1.124 MJ LHV of heat while the smallest amount of heat is from gas, that is 0.566 MJ LHV. Silver beneficiation has significant energy consumption, less than for gold beneficiation and greater than for copper. Copper and zinc beneficiation show similar characteristics.

The IMPACT 2002+ method analyses the life cycle impacts of a product, process, or a system of processes based on endpoint indicator

Table 4
Comparative LCA results of beneficiation process-CED method.

Impact category	Unit	Copper	Gold	Lead	Silver	Zinc
Renewables	MJ LHV	4.988	17,551.69	1.368	299.719	2.092
Fossil fuels - oil	MJ LHV	3.365	12,190.47	0.923	208.087	1.411
Fossil fuels - gas	MJ LHV	2.064	8903.549	0.566	151.659	0.865
Fossil Fuels - coal	MJ LHV	4.099	15,431	1.124	263.271	1.719
Biomass	MJ LHV	2.934	11,756.8	0.804	200.43	1.23
Nuclear	MJ LHV	15.66	54,965.26	4.295	938.637	6.567
Embodied energy LHV	MJ LHV	33.112	120,798.3	9.082	2061.798	13.88
Embodied energy HHV	MJ HHV	33.709	123,234.2	9.246	2103.316	14.13

based categories. The endpoint-indicator based categories are human health, ecosystems quality, climate change, and resources. The human-health impacts from the gold beneficiation are 0.018758 DALY where from lead beneficiation it is 1.46E-06 DALY. The ecosystems quality impacts from the gold beneficiation are 64,910.84 PDF $*$ m^2 $*$ yr where from lead beneficiation it is 5.064 PDF $*$ m^2 $*$ yr. The resources impacts from gold beneficiation are 8.59E-03 MJ primary where from lead beneficiation it is 6.61E-07 MJ primary. The climate change impacts from gold beneficiation are 3501.226 kg CO_2 eq where from the lead beneficiation it is 0.256 kg CO_2 eq. The comparative analysis based on this method shows here that among the five metals, the gold beneficiation process predominates on the endpoint indicator based categories. The lead beneficiation process shows the greatest sustainability among the co-product metals. The analysis results are presented in Table 5 and Fig. 6.

Previous research assesses the environmental impacts caused by the gold mining processes showed that due to a lower ore grade, gold mining consumes a huge amount of electricity, thus has large greenhouse gas effects (Chen et al., 2018; Haque and Norgate, 2014; Norgate and Haque, 2012). The major contribution of the present research is that this research specifically focuses on the metal beneficiation process, where most of the existing studies considered the whole mining process as a unit process. It is very crucial to identify the energy-intensive or environmentally detrimental process to assess the renewable-energy integration potential in a process (Farjana et al., 2018b). Also, this work considers >15 major impact categories, which lacks focus in previous work, mostly based on greenhouse-gas emissions, energy demand, and acidification. Of course, those are very important impact categories, but the greater environmental effects from these non-ferrous metals are on the ionising radiation field, which is a notable finding from this work. Table 6 shows the detailed life cycle emissions which are responsible for affecting a specific impact category in the combined metal beneficiation process. For climate change, carbon dioxide biogenic and carbon dioxide fossil are responsible for the highest emissions. Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114 emission is responsible for causing ozone depletion. Similarly, mercury is for human-toxicity non-cancer effects and chromium is for human toxicity cancer effects. Ammonia and

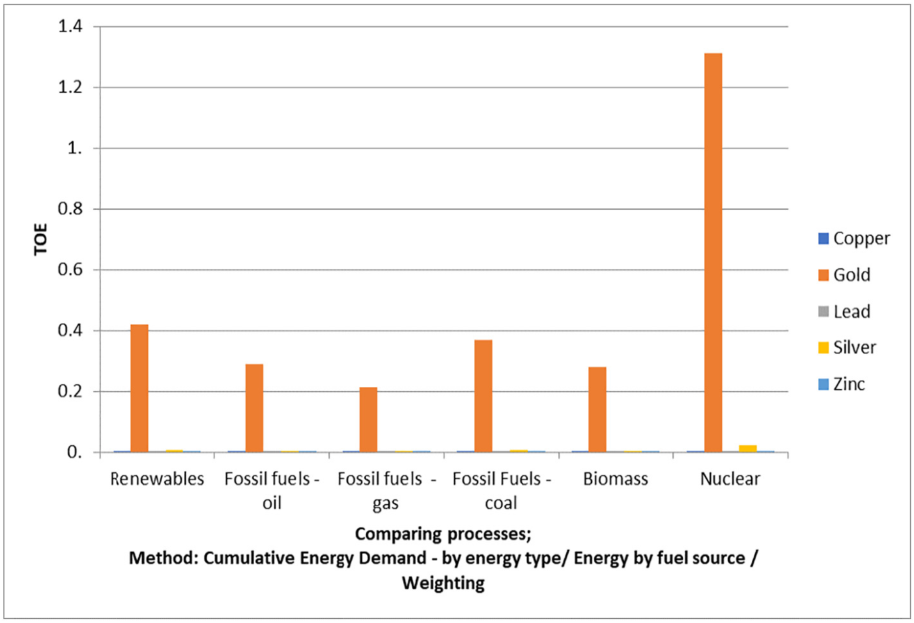

Fig. 5. Analysis results from CED method (weighted results).

nitrogen oxides are affecting particulate matter, acidification potential, metal depletion, and terrestrial eutrophication. Carbon and cesium emissions cause the ionising radiation effects on human-health and ecosystems. Phosphate is affecting freshwater ecotoxicity. In comparison among the coproduct metals, gold mining emits the largest amount of carbon dioxide, ammonia, nitrogen dioxides, and chromium. On the other hand, Lead beneficiation shows the greatest sustainability among all the coproduct metals.

4.1. Sensitivity analysis based on electricity mix and energy mix

Table 7 shows the sensitivity analysis results particularly focused on the beneficiation of gold. Five different case scenarios are considered here.

Grid mix 1- the Base case with medium voltage electricity for Sweden.

Grid mix 2- the Modified case with medium voltage electricity for CENTREL (Central European Power Association).

Grid mix 3- the Modified case with medium voltage electricity for NORDEL (Nordic countries power association).

Grid mix 4- the Modified case with medium voltage electricity for RER (Europe).

Grid mix 5- the Modified case with 50% reduction of hard coal, 50% reduction of diesel fuel and replacement of the equivalent amount of energy supply by natural gas.

Among the analysis results presented here, scenarios 2, 3, and 4 show a significant increase in climate change, but nearly unchanged results of terrestrial eutrophication, ozone depletion, and freshwater eutrophication, but surprisingly, much-reduced impacts in the fields of ionising radiation and human toxicity. On the other hand, scenario 5, that shows the effects of reducing 50% of coal consumption and 50% of diesel consumption and replacing the heat produced by them with natural gas, shows that the climate change, eutrophication (terrestrial and freshwater), acidification effects will be reduced a little bit with no significant change in ionising radiation. It is clear from the sensitivity analysis results that electricity consumption is the dominant factor for gold beneficiation. The sensitivity analysis conducted here reveals three basic facts. The first is the applicability of the dataset if the same technological mining principles are used but in the different regions with separate grid mix in European countries. The results from scenarios 2, 3, and 4 show that impact-analysis results are similar within the medium-voltage electricity grid mixes within Europe, even though the life cycle inventory datasets are particularly based on mines in Sweden. Another important fact from scenario 2, 3, and 4 is a modification of electricity grid mix acts oppositely among ionising radiation and climate change. Even though the climate change effects increase in some cases, ionising radiation decreases. Thirdly, scenario 5 shows the energy mix scenario by replacing coal and diesel with natural gas. This case shows the minimal change in environmental impacts can be caused by fossil fuel replacement since electricity consumption is not reduced which is the most crucial factor for the non-ferrous metal beneficiation process. In the case of metals assessed here other than gold, there are few types of research reported in the literature which tried to attempt a life cycle impact analysis of copper or zinc production processes, but none in the open literature about lead or silver production (Memary et al., 2012; Norgate et al., 2007; Norgate and Rankin, 2000; Qi et al., 2017). Previous researches on copper or zinc lack significant impact categories like ionising radiation, eutrophication, ecotoxicity, and human toxicity. This is another key feature of the present paper.

Table 5
Comparative LCA results of beneficiation process - IMPACT 2002+ method.

Damage category	Unit	Copper	Gold	Lead	Silver	Zinc
Human health	DALY	5.32E-06	0.018	1.46E-06	3.2E-04	2.23E-06
Ecosystem quality	PDF $*$ m^2 $*$ yr	18.463	64,910.84	5.064	1108.453	7.743
Climate change	kg CO_2 eq	0.935	3501.226	0.256	59.739	0.392
Resources	MJ primary	2.41E-06	8.59E-03	6.61E-07	1.47E-04	1.01E-06

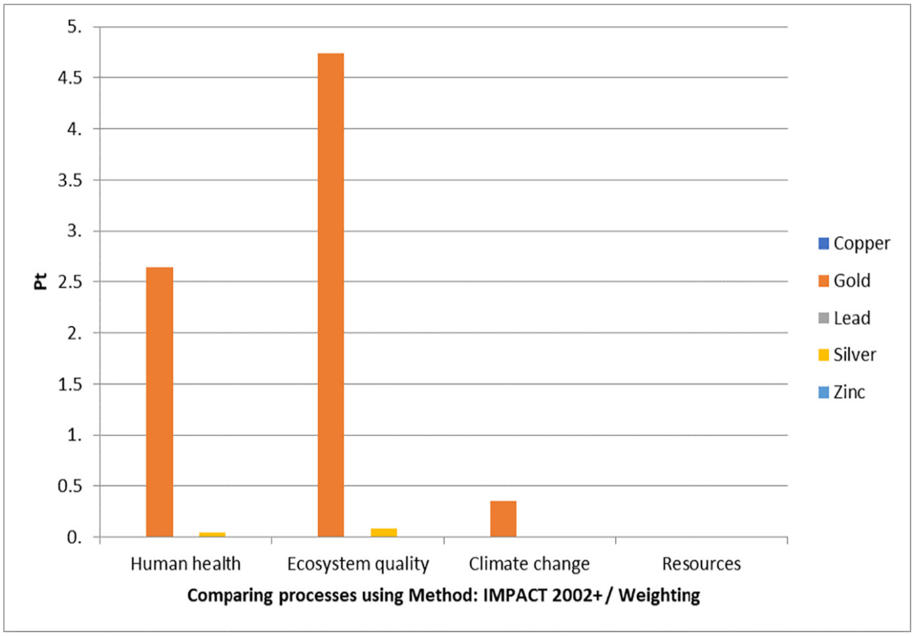

Fig. 6. Analysis results from the IMPACT 2002+ method (weighted results).

5. Discussion

This section discusses the comparison of results of the previous researches on the life cycle assessment of copper, gold, and zinc mining processes with the present study. This section also highlights the current techniques of environment-friendly beneficiation processes and discuss the future scope of energy integration in mining processes.

5.1. Comparison with previous studies

Table 8 compares among the GHG emission results from the previous studies on LCA of mining (copper, gold, lead, silver, and zinc) and this research. However, the research scope, system boundary, analysis method, geographic region consideration, allocation technique, energy mix, and heat mix vary among the studies, even though the studies are conducted for the same metal. The results are compared only concerning GHG because most of the previous studies did not conduct a full LCA, which makes it harder to compare for all the major environmental impact categories. The comparison shows that for copper mining, the greenhouse gas emission estimation ranges between 1.5 and 8.9 kg CO_2 eq./kg depending on those factors outlined above. From the current study, the calculated GHG emission result is 0.97 kg CO_2 eq., which agrees well with the previous studies within a reasonable limit. The major reason behind the variation is, the current study only

Table 6
Life cycle inventory emissions responsible for causing environmental effects per impact categories.

Impact category	Substance	Unit	Copper	Gold	Lead	Silver	Zinc
CC	Carbon dioxide, biogenic	kg CO_2 eq	0.279328	983.1072	0.076617	16.78781	0.117146
	Carbon dioxide, fossil	kg CO_2 eq	0.236714	937.5583	0.06493	15.98579	0.099277
OD	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	kg CFC-11 eq	2.87E-08	0.000101	7.88E-09	1.72E-06	1.2E-08
	Methane, bromotrifluoro-, Halon 1301	kg CFC-11 eq	3.14E-08	0.000112	8.61E-09	1.9E-06	1.32E-08
HTNCE	Mercury	CTUh	5.74E-09	4.01E-05	1.57E-09	6.8E-07	2.41E-09
	Mercury	CTUh	5.29E-09	2.84E-05	1.45E-09	4.82E-07	2.22E-09
HTCE	Chromium VI	CTUh	8.42E-10	2.95E-06	2.31E-10	5.05E-08	3.53E-10
	Chromium VI, ground	CTUh	4.76E-09	1.77E-05	1.31E-09	3.02E-07	2E-09
PM	Ammonia	kg PM 2.5 eq	0.000456	1.600453	0.000125	0.027331	0.000191
	Nitrogen oxides	kg PM 2.5 eq	0.000288	1.012937	7.9E-05	0.017297	0.000121
IRHH	Carbon-14	kBq U235 eq	0.577562	2025.006	0.15842	34.58137	0.242221
IRE	Carbon-14	CTUe	4.09E-06	0.014337	1.12E-06	0.000245	1.71E-06
	Cesium-137	CTUe	1.13E-06	0.003952	3.09E-07	6.75E-05	4.73E-07
POF	Nitrogen oxides	kg NMVOC eq	0.039907	140.296	0.010947	2.395772	0.016737
	NMVOC, non-methane volatile organic compounds	kg NMVOC eq	0.007103	24.92484	0.001948	0.425641	0.002979
AP	Ammonia	molc H+ eq	0.020663	72.4643	0.005668	1.237482	0.008666
	Nitrogen oxides	molc H+ eq	0.029531	103.8191	0.0081	1.772871	0.012385
TE	Ammonia	molc N eq	0.092368	323.9298	0.025337	5.531789	0.038739
	Nitrogen oxides	molc N eq	0.170003	597.6611	0.046632	10.20599	0.071299
FE	Phosphate	kg P eq	0.000803	2.821253	0.00022	0.048178	0.000337
ME	Nitrogen oxides	kg N eq	0.015524	54.57516	0.004258	0.931955	0.006511
FE(Ecotox)	Antimony	CTUe	0.004578	62.8252	0.001256	1.061984	0.00192
	Chlorothalonil	CTUe	0.023869	83.74461	0.006547	1.430108	0.010011
LU	Occupation, dump site	kg C deficit	0.074997	263.6401	0.020571	4.502064	0.031453
	Occupation, forest, extensive	kg C deficit	0.33132	2949.001	0.090879	49.94369	0.138951
WRD	Water, cooling, unspecified natural origin/m^3	m^3 water eq	0.001448	6.017579	0.000397	0.102544	0.000607
	Water, river	m^3 water eq	0.003435	12.08332	0.000942	0.20634	0.001441
MERED	Gas, mine, off-gas, process, coal mining/m^3	kg Sb eq	1.88E-14	6.69E-11	5.15E-15	1.14E-12	7.87E-15

Table 7
Sensitivity analysis results of gold beneficiation.

Impact category/gold	Grid mix 1 - SE	Grid mix - CENTRAL	Grid mix 3 - NORDEL	Grid mix 4 - RER	Grid mix 5 - energy mix	Unit
CC (climate change)	3640.552	12,617.75	14,056.23	8142.061	3473.757	kg CO_2 eq
OD (ozone depletion)	0.00022	0.00018	0.0001	0.0002	0.0002	kg CFC-11 eq
HTNCE (human toxicity, non-cancer effects)	0.00038	0.00072	0.0003	0.0004	0.0003	CTUh
HTCE (human toxicity, cancer effects)	2.37E-05	0.000118	2.36E-05	4.02E-05	2.29E-05	CTUh
PM (particulate matter)	10.697	10.624	7.944	9.38	10.179	kg PM 2.5 eq
IIHH (ionising radiation HH)	2148.905	852.482	0.289	1452.374	2148.86	kBq U235 eq
IIE (ionising radiation E)	0.0194	0.00769	1.67E-06	0.013	0.0194	CTUe
POF (photochemical ozone formation)	172.22	188.807	198.357	180.182	169.3	kg NMVOC eq
AP (acidification)	191.714	245.336	208.237	215.203	187.484	molc H+eq
TE (terrestrial eutrophication)	951.064	1008.62	1058.83	978.379	940.453	molc N eq
FE (freshwater eutrophication)	2.844	2.833	2.841	2.834	2.844	kg P eq
ME (marine eutrophication)	59.255	64.556	69.298	61.78	58.28	kg N eq
FE (freshwater ecotoxicity)	1193.144	2731.087	1147.639	1656.817	1165.771	CTUe
LU (land use)	3335.388	3041.193	2283.141	2913.374	3313.839	kg C deficit
WRD (water resource depletion)	19.88	65.699	11.752	41.269	19.82	m^3 water eq
MFRRD (mineral, fossil & ren resource depletion)	6.69E-11	5.67E-11	4.95E-11	1.49E-10	6.63E-11	kg Sb eq

considers the copper beneficiation process where most of the previous studies considered the entire mining process.

Another key point to be noted is economy-based allocation technique is considered in this study, whereas most of the previous studies considered mass based allocation. The overall impact of zinc in GHG values in per tonne of zinc production reported in the previous studies agrees very well with the current research. For gold mining, previous studies reported that GHG varies between 180 t CO_2 eq./kg Au which was based on hybrid allocation based on both mass and economy. This research only considered economy-based allocation which obviously yields more turnover of environmental impacts on gold beneficiation due to its high value. For silver and lead, no significant research output is reported in the open literature based on the environmental impacts through life-cycle assessment.

5.2. Environment friendly beneficiation processes in practice

Environmentally sustainable beneficiation processes are currently in practice or under development not only for gold-silver-lead-zinc-copper but also for other metals. This sustainable production processes can reduce chemical emissions and can promote greater sustainability to the environment. Birich et al. presented an alternative production route for silver extraction which will separate around 60% of non-silver minerals, and afterwards, nitric acid leaching will produce silver with concentrations up to 98%. The silver is separated through copper cementation (Birich et al., 2018). Andrea et al. presented a novel approach for rare earth metal separation in Europe through separation based on Eudealyte (Schreiber et al., 2016). Azimi et al. presented a dry coal beneficiation method, which would reduce the environmental burdens (Rajender Gupta, 2014). Edy et al. presented bio flotation techniques for iron and sulphur, which is based on bacteria and mineral interaction for sustainable production of minerals (Sanwani et al., 2016). Ergin et al. presented environment-friendly optical separation of minerals like lignite which could reduce the environmental impacts (Gülcan and Gülsoy, 2017). Natalya et al. presented two-step hydrometallurgical technique to reduce the environmental emissions from copper zinc concentrate processing (Fomchenko and Muravyov, 2018). Natarajan et al. studied biotechnology, microbial, and bioleaching based beneficiation process of metals (Natarajan, 2006). A similar study has been conducted by Silva et al. and Sukla et al. for metal extraction and beneficiation (Behari et al., 2014; Silva et al., 2017). Lijun et al. presented pumped storage based coal beneficiation which would increase the energy efficiency of the coal mining (Zhang et al., 2014). There are more studies which are working to upgrade the flotation technique of metals and minerals which would result in sustainable production practices (Feng et al., 2017c, 2018a, c).

Table 8
Comparison of results from this study with the previous studies.

Metal	Study	GHG emission results
Copper	Norgate (Norgate and Rankin, 2000)	3.3 kg CO_2 eq./kg
	Memary et al. (Memary et al., 2012)	2.5 to 8.5 kg CO_2 eq/kg
	Norgate (Norgate, 2001)	4.3 to 8.9 kg CO_2 eq./kg 1.5 to 4.2 kg CO_2 eq./kg
	Northey et al. (Northey et al., 2013)	1 to 9 t CO_2 eq./Cu
	This research	0.97 kg CO_2 eq.
Gold	Chen et al. (Chen et al., 2018)	5.55E7 kg CO_2 eq
	Norgate et al. (Norgate and Haque, 2012)	18,000 t CO_2 eq./t Au
	This research	3640.55 kg CO_2 eq
Zinc	Genderen et al. (Van Genderen et al., 2016)	2600 kg CO_2 eq./t
	Qi et al. (Chen et al., 2018)	6.12E3 kg CO_2 eq.
	This research	0.41 kg CO_2 eq.
Silver	This research	62.12 kg CO_2 eq.
Lead	This research	0.268 kg CO_2 eq.

5.3. Limitations and future recommendations

According to the findings of the present study, the major source of the environmental impact of metal beneficiation process is energy consumption in the form of fossil fuel for electricity generation and the blasting process. Carbon-14 emission from medium-voltage electricity generation is responsible for ionising radiation. On the other hand, blasting releases nitrogen oxides and zinc; this causes photochemical ozone formation, terrestrial eutrophication, marine eutrophication, human toxicity (non-cancer effects), and acidification. Replacing fossil fuels through renewable energy resources would be a great solution to reduce these environmental burdens. A sensitivity analysis presented in this paper (Table 7) showed that different electricity grid mix with more non-fossil fuels could significantly reduce the environmental effects of gold beneficiation. Energy integration can be done by replacing the electricity generation sources or replacing the process heat generation resources. Solar industrial process heating systems are already in operation for mining industries in Chile, South Africa, and Oman (Farjana et al., 2018c). Many other research works are already in progress to access the prospect of energy efficiency and energy integration in mining industries (Eglinton et al., 2013; Günter and Colin, 2016; Paraskevas et al., 2016). Though energy integration would be a great sustainability solution for the mining sector, it implies the demerits of significant capital cost, and the availability of renewable energy during off-peak hours (Farjana et al., 2018e,f). To avail the renewable energy sources, additional energy storage systems could be utilized that can also impose a larger capital cost.

In summary, the recommendation of this paper is to integrate renewable energy generation systems into the metal beneficiation and flotation processes. Further assessment is required to analyse the

feasibility of the energy integration, process integration, and life cycle cost analysis (CAPEX and OPEX). This study provides invaluable information on the fact that metal beneficiation process is not only affecting global climate change but also is harmful to human health through ionising radiation effect to a great extent. However, the results reported in this study is based on only the economy-based allocation method which implies more weights to the environmental emission from gold beneficiation.

6. Conclusion

In conclusion, this paper presents and discusses the key factors that cause significant environmental impact due to gold-silver-lead-zinc-copper beneficiation process. The major environmental impact categories are analysed using the ILCD method, and the CED method. The primary reasons behind the environmental burdens associated during the beneficiation process are the blasting process and the amount of electricity consumption in the beneficiation process. From the analysis results presented in this paper, the gold and silver metal beneficiation processes are the most impactful towards environmental sustainability. Gold beneficiation is dominant over the other metals where ionising radiation has the highest impact. The improvement of energy-generation source grades and improvement in energy efficiency would be mostly helpful to reduce the environmental effects on human health, ecosystem, and biodiversity. Modification of the grade of the fuel resources or improvement of energy efficiency would be helpful to turn the beneficiation technologies into an environmentally friendly industrial processing route.

Nomenclature

kg CO_2 eq Carbon dioxide equivalent
kg CFC-11 eq Ozone Depletion Potential OZDP kg CFC-11 eq
CTUh Comparative Toxic Unit for human
kg PM 2.5 eq Unit for particulate matter
kg NMVOC eq non-methane volatile organic compounds equivalent
molc H+ eq Mole of Hydrogen equivalent
molc N eq Mole of Nitrogen equivalent
kg P eq kilograms of Phosphorus equivalent
kg N eq kilogram of Nitrogen equivalent
CTUe Comparative Toxic Unit for ecosystems
M^3 H_2O Volume of water supply
kg Sb eq kilogram of Antimony equivalent
kg SO_2 eq Kilogram of sulphur di oxide equivalent
kg O_3 eq Kilogram of ozone equivalent
DALY Disability adjusted life year.
$PDF * m^2 * yr$ Potentially Disappeared Fraction of species over a certain area over a certain time
MJ primary Total life cycle ***primary*** energy use

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